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New digital techniques applied to A and Z identification using Pulse Shape Discrimination of Silicon detector current signals.

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Abstract

Extending Pulse Shape Discrimination (PSD) to digitized signals is one of the most promising methods to identify particles stopped in a detector. Using the CIME accelerator in the GANIL laboratory, a measurement campaign was done to collect data corresponding to different charges, masses and energies of implanted ions. These data are used to develop an algorithm capable to discriminate the different particles both in mass and charge. In this experiment, a 300 μm n-TD reverse mounted Si-Detector was used. These studies on PSD are part of the FAZIA R&D,

a research and development project aiming at building a new 4π array for isospin nuclear physics.

Key words: Pulse Shape Discrimination, PSA, Silicon detector, Current signal, PACI

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1 Introduction

1 With respect to the first 4π arrays devoted to charged particles conceived
2 in the 80's, progresses in detection apparatuses have permitted in the 90's
3 the advent of compact 4π powerful devices [1] which allowed to improve the
4 experimental study of the multifragmentation of highly excited nuclear sys-
5 tems, possibly connected to a first order phase transition in nuclear matter
6 [2]. With the rapidly expanding number of Radioactive Ion Beam accelera-
7 tors, the possibility is offered of studying also the isospin (N/Z) dependence
8 of the Nuclear Equation of State (EOS). For this purpose, the range of the
9 identified mass number A with a compact geometry has to be extended and
10 low thresholds for A and Z identification are necessary; developments of tech-
11 niques toward a third generation of 4π multidetectors are necessary [2]. One
12 of the new proposed devices is FAZIA [3], a high granularity 4π apparatus
13 for charged reaction products, planned to operate in the field of heavy-ion
14 induced collisions below and around the Fermi energy (10-100 MeV/nucleon).
15 FAZIA will be designed to study Thermodynamics and Dynamics of excited
16 exotic nuclei, exploring for example the isospin, temperature and density de-

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17 pence of the EOS symmetry energy term [2]. In order to reach the best
 18 performances, this detector will exploit the development of digital electronics.
 19 In fact, by using high frequency Analog to Digital Converters, it is now possi-
 20 ble to implement a fully digital processing of the signals produced by detected
 21 particles and perform (possibly on-line) identification by using Digital Signal
 22 Processor techniques. With such components which can be integrated in a
 23 compact way, one expects to be able to build new detectors with better angu-
 24 lar resolution, better mass discrimination and lower identification thresholds.
 25 Using digital electronics, the mass number (A) and atomic number (Z) identi-
 26 fication via Pulse Shape Discrimination (PSD) can be envisaged in a new and
 27 more complete approach. PSD is not a new technique (see, for example, [4]
 28 and the following studies in relation with its application inside a 4π silicon ball
 29 detector [5,6,7,8]), but as recent studies have demonstrated [9,10,11], we have
 30 now the possibility to perform it in a fully digital way. Through the PSD in
 31 the first detection layer, we will be able to decrease the identification threshold
 32 with respect to the standard ΔE -E telescope technique which requires that
 33 particles have enough energy to punch through the ΔE detector. Simplifying
 34 and automating the calibration procedure is also essential as the number of
 35 detectors is becoming larger and larger for highest granularity and angular cov-
 36 erage. In order to study and possibly improve PSD algorithms, a measurement
 37 campaign was performed using the CIME cyclotron in the GANIL laboratory.
 38 In this paper, we report on new results concerning the mass number identi-
 39 fication of ions stopped in a Silicon detector by using Pulse Shape Analysis
 40 on the current signal. We found that, at energies around $E/A = 8\text{MeV}$, it
 41 is possible to fully identify the mass number for carbon isotopes, while from
 42 Argon up to Krypton isotopes, the mass number resolution can be considered,

at least for the moment, of about 2-3 mass units.

2 EXPERIMENTAL SETUP

The measurements were performed at GANIL using the ions accelerated by the CIME cyclotron. In this experiment we have decided to concentrate our attention on the current signal produced by the detected particle. The Si-Detector, collimated at 10 *mm* diameter, was mounted on a mechanical support and placed directly inside the beam line to collect the ions without the needs of any target. The detector used was a 300 μm thick n-TD silicon (200 *mm*² as active area) mounted in a reverse configuration (rear contact as entrance window and hence lower electric field). The shape of current signals from solid state detectors is mainly governed by the combination of plasma erosion time and charge carrier collection time effects. In contrast to front-side injection, the reverse-side configuration amplifies the plasma-time differences: for ions of a given energy, an enhanced dependence of the risetime and of the whole signal is expected and observed indeed when using reverse mount configuration([5],[12]). The applied voltage was fixed at a value of 190 *V* during the experiment, while the depletion voltage for this detector was 140 *V*. The energy of the beam was such that the ions were always stopped in the detector and the beam spot was of about 3 *mm* in diameter. The pre-amplifier used in the experiment was the low-gain-version of the PACI described in [9]: it provides two outputs, proportional to the charge and the current produced by the detected particle. It was mounted as close to the detector as possible (4 *cm*) inside the vacuum chamber. This solution will be applied also in the FAZIA project, to avoid signal degradation. The PACI current output was

67 sent to an ACQIRIS acquisition system [13], which is a commercial 8 bit dig-
 68 itizer sampling at 2 GHz . All the signals from the different ions were stored
 69 using the same amplitude scale on the ACQIRIS system, so they are directly
 70 comparable. The PACI charge output was sent to standard shaping analogue
 71 electronics to measure the energy with a peak-sensing ADC. In the following
 72 the energy measurements always refer to this kind of determination. The trig-
 73 ger was done using the fast output of the charge amplifier and a proper trigger
 74 logic permitted to acquire, for each event, both the whole current signal and
 75 the shaped energy from the peak-sensing ADC. The energy of the beam in
 76 the experiment varied from 7.39 $AMeV$ to 8.68 $AMeV$ and the species of
 77 accelerated ions covered a somewhat wide range, from ^{12}C up to ^{84}Kr . The
 78 cocktail beam measured energy in Fig. 1, for example, was obtained with a
 79 single mixed source and a given setting of the cyclotron. In these conditions
 80 the Argon intensity was mainly optimized, with many other elements present
 81 in smaller quantities. All of them have the same final velocity, provided that
 82 the effective charge to mass ratio remains the same. Several runs were done
 83 corresponding to different settings of the cyclotron. During our experiment,
 84 we were working with a "mixed" beam with known effective charge allowing a
 85 very good velocity resolution (of the order of few 10^{-3}), but the corresponding
 86 absolute value was only known within about $\pm 1\%$. In Fig.1, one can see the
 87 ADC spectrum where each peak corresponds to a different accelerated isotope,
 88 all having $q/A = 0.25$ and energy of $E/A = 8.68 AMeV$. For the following
 89 analysis in order to select different ions, on each energy peak we made an
 90 energy selection by imposing a cut centred on the most probable value (with
 91 $\pm 0.5\%$). It would be very interesting to work in the future at smaller incident
 92 energies and to explore the lower energy limit of the PSD method presented
 93 in this article.

95 The first step of data analysis was the total energy ADC calibration (see Fig.
 96 2) in order to determine the mass number of the detected particle. Knowing
 97 the effective charge and the composition of the mixed source, it was possible
 98 to identify the different ions present in each experimental run before applying
 99 the PSD technique. For this calibration, 22 points were used, corresponding
 100 to all the available ions and energies except for the Kr-ions which are affected
 101 by the Pulse Height Defect (PHD). Fig. 3 shows different signals from our
 102 database. Inside the database, it was possible to find 3 pairs of isotopes with
 103 quite similar total energy : ^{12}C at 98.54 *MeV* versus ^{13}C at 96.75 *MeV*; ^{36}Ar
 104 at 313.92 *MeV* versus ^{40}Ar at 312.88 *MeV* and ^{80}Kr at 688.43 *MeV* versus
 105 ^{84}Kr at 676.18 *MeV*. Their energies are different by 1.82%, 0.33% and 1.78%
 106 respectively. This can slightly affect the results shown in this paper, but all
 107 the methods tested in the following are strictly applied on the same selected
 108 groups of events, so that the relative comparison between them is not affected
 109 by this problem. The first attempt to obtain a mass discrimination was done
 110 by looking at the distribution of the most simple and easiest parameters to
 111 extract (see Fig. 4): the signal amplitude, the risetime (i.e. the time needed
 112 to raise from 10% up to 90% of the amplitude), the decay time (i.e. the time
 113 needed in the second part of the signal to decrease from 90% to 10% of the
 114 amplitude) - both last calculations using an interpolation of the signal in order
 115 to improve the time resolution (see [14]) - and the 'rising-slope' (i.e. the angular
 116 coefficient of the linear interpolation between the point of 10% and the point
 117 of 90% of the signal). In Table 1, we report the separation obtained for each
 118 tested method by fitting, for each pair of isotopes, the distribution of signal

119 amplitude, risetime, etc... with two gaussians. Starting from the parameters
 120 of these fits, we can define the Factor of Merit M ([15]) as:

$$M = \frac{|\mu_1 - \mu_2|}{(\sigma_1 + \sigma_2) * 2.35} \quad (1)$$

121 where μ_1 and μ_2 are the centroids and σ_1 and σ_2 are the standard deviations
 122 of the two gaussian fits corresponding to the selected pairs of Carbon, Argon
 123 and Krypton isotopes. With this definition, the better is the discrimination,
 124 the larger the Factor of Merit. Usually one assumes that satisfactory discrimi-
 125 nation is obtained for $M > 0.75$ (rejection ratios for one ion with respect to the
 126 other of 12.5:1, [15]). According to this criterion, Table 1 shows that signal
 127 amplitude gives good results for Carbon and Argon, but it is not completely
 128 satisfactory for Krypton. Therefore, the use of “richer” parameters (or correla-
 129 tions among them) is needed to have a better separation in particular between
 130 the Kr isotopes. High order moments of the time distribution of the current
 131 signal, which take into account the whole sampled signal -i.e. the whole infor-
 132 mation available-, will be used in the following. A first step in this direction
 133 was shown in [9], where the second moment m_2 of the time distribution of the
 134 current signal is used in order to separate two isotopes of carbon (^{12}C and
 135 ^{13}C) at 80 MeV. As one can see in Table 1, the m_2 method is not able to
 136 discriminate the heaviest ions. As we will explain in this paper, it is possible
 137 to improve this result by exploiting the correlation between the second and
 138 the third moment. In order to extract the samples $f[i]$ of the current signal
 139 for the numerical analysis, one has first to subtract the baseline, which is a
 140 slightly fluctuating quantity from one event to the other. For each event, i.e.
 141 for each sample sequence, the mean baseline is obtained by averaging the first
 142 400 samples preceding the very onset of the signal. Therefore, starting from

143 the sampling $s[i]$ provided by the ACQIRIS system, we can define the current
 144 signal $f[i]$ as:

$$145 \quad f[i] = s[i] - b \quad (2)$$

146 where b is the mean baseline. In the formulae (4)-(5), the signals are rescaled
 147 to start with the first sample at $t = 0$. There is also a conversion factor on the
 148 time axis of to have the samples i expressed in ns (as the sample frequency
 149 is 2 GHz). In order to have also the different moments of the distribution
 150 expressed in ns and to compact the scale, we have extracted the $1/k^{th}$ root
 151 for each high order moment. For convenience, we will label them as usual
 152 mathematical moments. By taking into account the modifications introduced
 153 in the calculation of the different moments of the signal, the formulae become:

$$154 \quad m_0 = \sum_{i=start}^{istop} f[i] \quad (3)$$

$$155 \quad m_1 = \sum_{i=start}^{istop} \frac{f[i](i - start)0.5}{m_0} \quad (4)$$

$$156 \quad m_k = \left| \sum_{i=start}^{istop} \frac{f[i] [0.5(i - start) - m_1]^k}{m_0} \right|^{1/k} \quad (5)$$

157 where i is the i^{th} sampling point of the signal. The sum is done between a
 158 start, that is the first sampling point where the signal is higher than the fixed
 159 threshold with respect to the mean baseline (i_{start}) and a stop, that is the
 160 sampling point where the signal becomes smaller than the same threshold
 161 (i_{stop}). The threshold thus defines the zone where the samples are assumed to
 162 correspond to real signals. Considering the strong asymmetry of our current
 163 signals, the averaged value of m_1 in the configuration $f[i]$ is not centred with
 164 respect to the time extension of the signal, while the higher order moments

defined by (5) are indeed “centred moments”, i.e. they are calculated with respect to the distribution centroid. In order to study the discrimination efficiency of the moments method applied to a signal for which the m_1 will be more centred with respect to the time extension, we proceeded in the following way: we define another sequence ($data[i]$) related to the current signals:

$$data[i] = C_{baseline} - f[i] \quad (6)$$

where $C_{baseline}$ is a fixed constant for each pair of ions, greater than the amplitude of the analysed signal in order to keep always the signal completely positive (so that the meaning of moments is preserved). In the upper part of Fig.5, the averaged signals for the 3 pairs of ion are shown in configuration $f[i]$. In the bottom part of Fig.5, the m_1 distribution with the signal expressed as $data[i]$ with different values of $C_{baseline}$ is compared to the m_1 distribution with the signal expressed as $f[i]$. The use of $data[i]$ configuration and the variation of $C_{baseline}$ has various influences in the moment calculation. In fact, it changes the position of m_1 , i.e. it varies the “centrality” of the moments. Moreover, since $data[i]$ is greater when $f[i]$ is smaller and vice versa, new weights are given to the various portions of the signal, namely the onset and the end of the signal have a higher influence on the so-calculated moments. As one can see in Table 2, by a proper selection of the constant $C_{baseline}$, we can find a value for which the averaged value of the m_1 is close to the middle of the duration time of the signal. Note that the m_1 distribution becomes also centred near the crossing point of the averaged signal corresponding to the different isotopes. These values of the constant $C_{baseline}$ are respectively around 100, 150 and 80 for Carbon, Argon and Krypton isotopes. Using $data[i]$ with the proposed value of $C_{baseline}$, we have a more equilibrated weight-sharing in

190 the calculation of the different moments between the two parts of the signal
 191 which are connected to the collection of the electrons (fast part of the signal)
 192 and the holes (slow part of the signal). This effect is more evident in the case
 193 of heavy ions, as Krypton, where the time duration of the current signal is
 194 longer and more asymmetric. Having verified that the distribution of a single
 195 moment (m_1 , m_2 , etc.) is not sufficient to provide the desired discriminations,
 196 we studied, for each ion pair at a given energy, the various correlations be-
 197 tween two moments. From all the examined cases, it appears that the best
 198 discrimination approach in our case is to use the second vs. third moment
 199 correlation. Working in this bi-dimensional plane, it is possible to achieve the
 200 best separation between the 3 selected pairs of ions, as one can see in the
 201 example shown in Fig.6, referring to Ar-isotopes. Looking at Fig.6, one can
 202 see that the directions of the major axis of the m_2 vs m_3 correlation for ^{36}Ar
 203 and ^{40}Ar are almost parallel. We observe basically the same behaviour for the
 204 other analysed ion pairs. Therefore we can obtain a more efficient separation
 205 by projecting the bi-dimensional plot along a direction perpendicular to the
 206 direction of the two major-axes of the distributions (x' in the Fig.6), once the
 207 necessary rotation of variables is applied:

$$x' = (m_2 - x_0)\cos\alpha + (m_3 - y_0)\sin\alpha \quad (7)$$

208 where α is the rotation angle between the old reference system (m_2, m_3) and
 209 the new reference system (x', y'), while $O'(x_0, y_0)$ is the new axis origin. Af-
 210 ter the projection, we can estimate the quality of the discrimination with the
 211 Factor of Merit M defined as before. In Figs. 7,8, one can see the projections
 212 corresponding to the 3 different pairs of ions ^{12}C vs ^{13}C , ^{36}Ar vs ^{40}Ar and ^{80}Kr
 213 vs ^{84}Kr using the *data[i]* configuration with the value of $C_{baseline}$ which opti-

214 mizes the Factor of Merit. In Table 3 the values coming out from a gaussian
 215 fit on the peak of Fig.7 and Fig.8 are shown, while in Table 4 are reported
 216 the corresponding Factor of Merit M for the two signal configurations, the
 217 standard one ($f[i]$) and the proposed one ($data[i]$). The improvement in the
 218 discrimination is quite evident, especially in the case of Krypton. By compar-
 219 ing this moment correlation method with the other simpler techniques (Table
 220 1), we observe that better results are always obtained, even reaching a sat-
 221 isfactory value of $M=1.04$ for the otherwise problematic case of Krypton. In
 222 Table 3 one can also see that, using $data[i]$, the Factor of Merit for Krypton is
 223 larger than for Argon. This is probably due to the fact that the current signals
 224 associated to Krypton are longer and more asymmetric than those of Argon.
 225 So that, the effect to use $data[i]$ instead of $f[i]$ is greater in the Krypton case
 226 with respect to the Argon case. In the light of the more recent measurement
 227 campaign performed by the FAZIA collaboration at the Laboratori Nazionali
 228 di Legnaro ([16], [17]), we should not forget that the $< 111 >$ Silicon detector
 229 used in the presently described experiment was not tilted, so that the presence
 230 of a not negligible fraction of events that have experienced the channelling ef-
 231 fect in a such relevant way to change the shape of the current signal should
 232 be considered. The ions channelled along the crystal major axis or planes, in
 233 fact, are leading to signals with a different shape as compared to those induced
 234 by ions impinging along random directions ([17]). Concerning the PSD results
 235 presented in Figs. 7 and 8, we suspect that channelled ions maybe responsible
 236 for the left tail visible for Carbon and Argon isotopes. For Krypton (Fig.8) the
 237 effect is not appreciable because the energy selection was done in the same way
 238 as for the other ions ($\pm 0.5\%$ with respect to the mean value), thus resulting
 239 in a more efficient way to remove a large fraction of the channelled ions: in
 240 fact, for heavy ions the "channelled" particles show a larger energy difference

with respect to the "random" ones ([17]), because the effect is mediated by Pulse Height Defect, increasing with ion charge for a given velocity.

4 CONCLUSION

Digital PSD is one of the most promising techniques to exploit when building new detectors with enhanced identification resolution. Through Digital PSD, it will be possible to decrease the identification threshold. Moreover, if one is able to perform the discrimination on-line, using fast on-board electronics, the following off-line calibration work can be also significantly reduced. In this paper, we have presented a new discrimination technique applied to the current signals produced in a n-TD Silicon detector by various heavy-ions fully stopped in the Silicon detector. The experiment was performed at GANIL in the early stage of the FAZIA collaboration. On the basis of the obtained Factor of Merit, one can say that the limit of the proposed technique is currently one mass unit separation in the region of Carbon ions and a separation of about 2-3 units of mass, in the Ar and Kr ion regions, for an energy of around $E/A = 8 \text{ A MeV}$. Other experiments have stressed the importance of carefully avoiding channeling effect ([16], [17]) and the necessity of using Silicon material with very uniform doping for PSD applications ([7],[18]). Taking into account these (partly new) results, the actual limit for the m_2 vs m_3 discrimination technique proposed in the article is expected to be prone for possible further improvements: one plans to verify this during the next experiments, where the problems concerning the channeling and the resistivity uniformity of the detector will be addressed and possibly solved. Using a wider mass and energy distribution (as planned in the next R&D FAZIA experiments), we

265 hope to adress the low threshold problem, i.e. the limitation of PSA. The data
 266 presented here do not allow to conclude on this specific point. Apart from
 267 the obtained results, we stress again that an interesting characteristic of this
 268 discrimination technique is the possibility of calculating - directly "on line"
 269 - the high order moments values m_2 and m_3 of the time distribution of the
 270 signals. In this way, one may avoid to store the whole signal (with the associ-
 271 ated problems of memory and data transfer) in order to obtain the mass and
 272 charge discrimination. The information will be condensed in some relevant pa-
 273 rameters, allowing to build two-dimensional maps as the m_2 vs m_3 discussed
 274 in this article, together with other ones, as for example the charge risetime vs
 275 energy plot as alternative to the standard Time of Flight-Energy technique.
 276 The presented technique has to be tested in a "real" experiment and not only
 277 with mono-energetic known A and Z beam. With a large distribution of masses
 278 and energies it is possible that the proposed technique has to be coupled to
 279 a more standard technique for element identification before to be applied to
 280 the data set: first a Z-identification through Rise Time versus Energy and an
 281 optimal choise of $C_{baseline}$ for each element (Eq.6), and then (m_2, m_3) -A identi-
 282 fication. Other works and more complete experiments are necessary to extend
 283 the ion database needed to improve and test this proposed PSD technique,
 284 which seems to be a very promising field of investigation.

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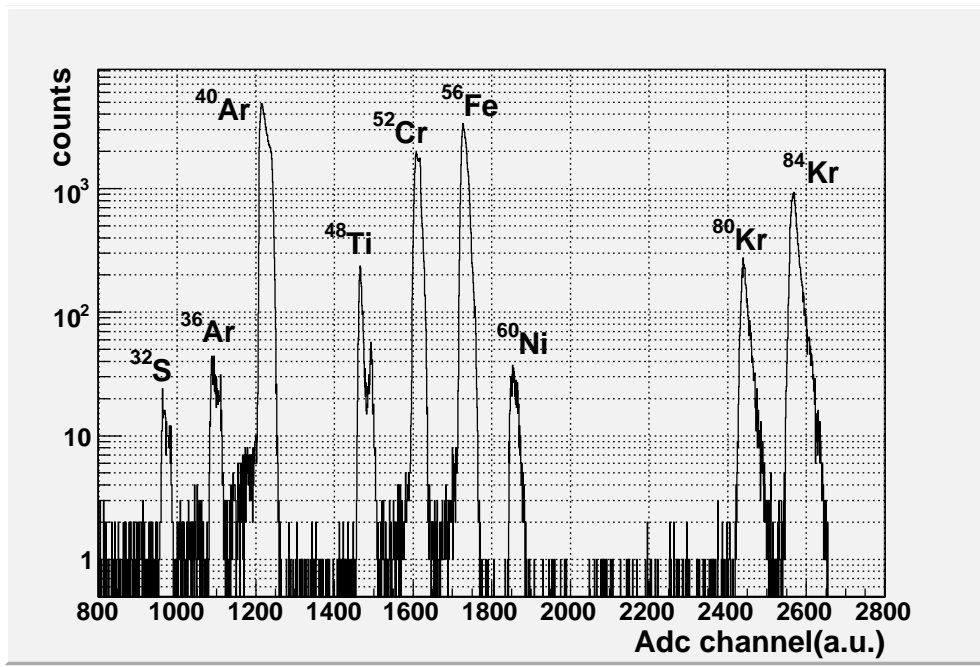


Fig. 1. ADC raw spectrum. One can see the different peaks corresponding to the different ions implanted in the detector ($q/A=0.25$).

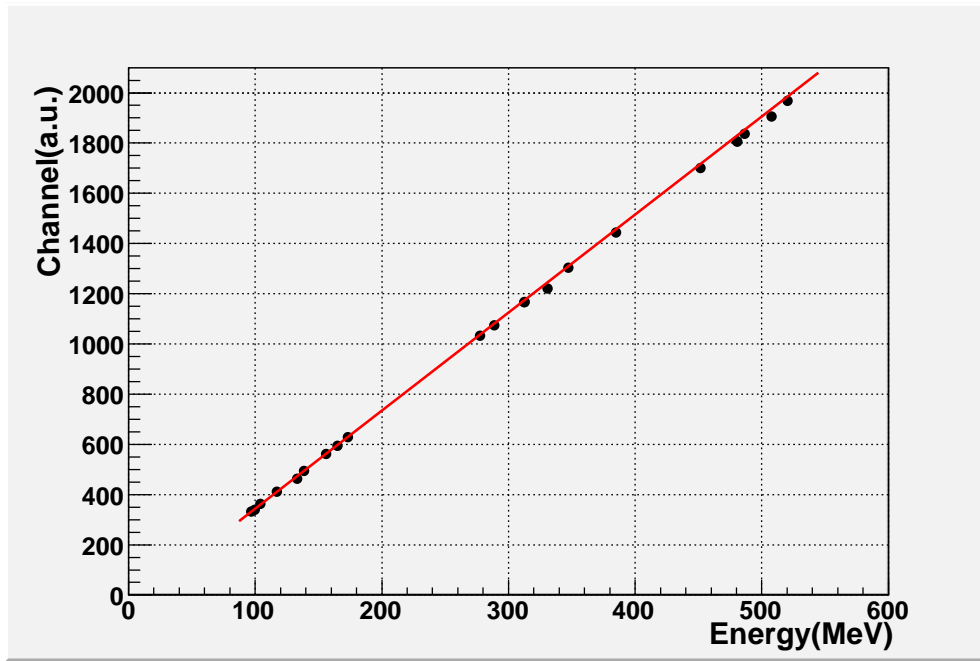


Fig. 2. Linear energy calibration of the ADC.

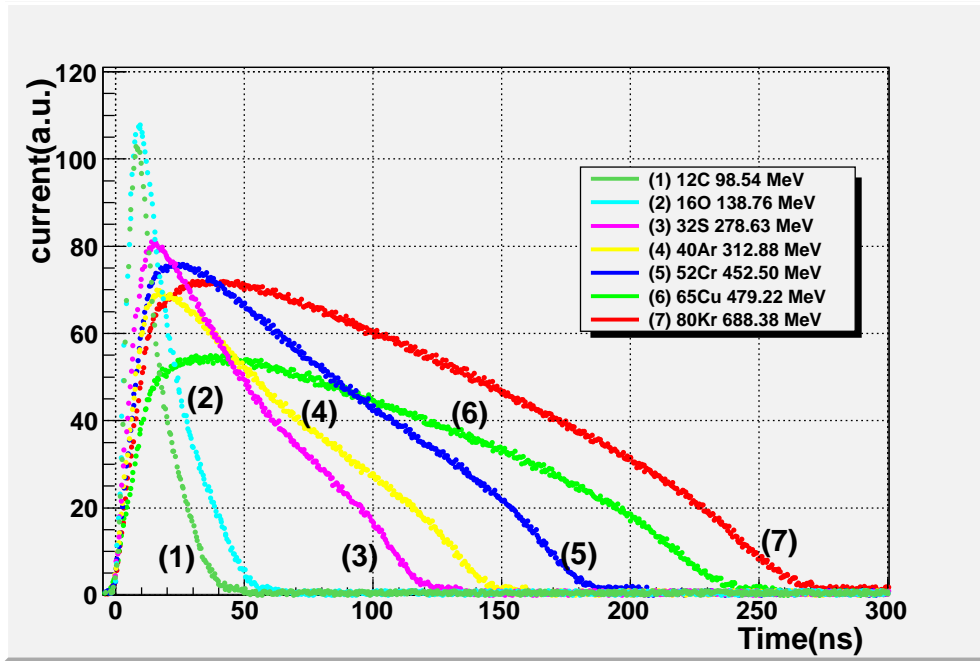


Fig. 3. Averaged signals (4000 events for each ion) corresponding to some ions of the database built after the CIME experiment.

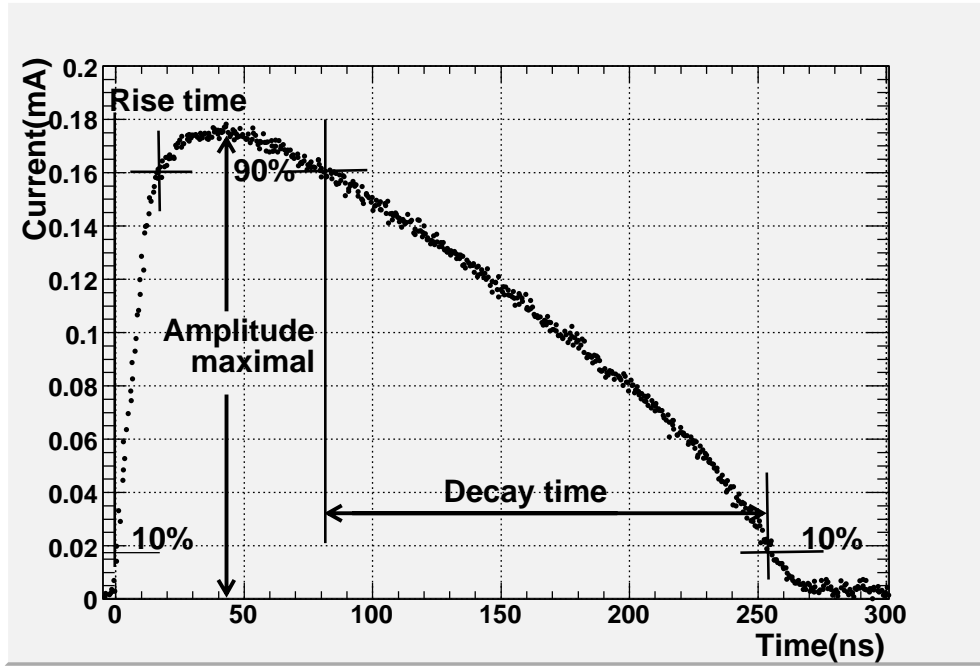


Fig. 4. Signal of ^{80}Kr @688 MeV on which one can easily see the definition of the risetime, decay time and signal amplitude.

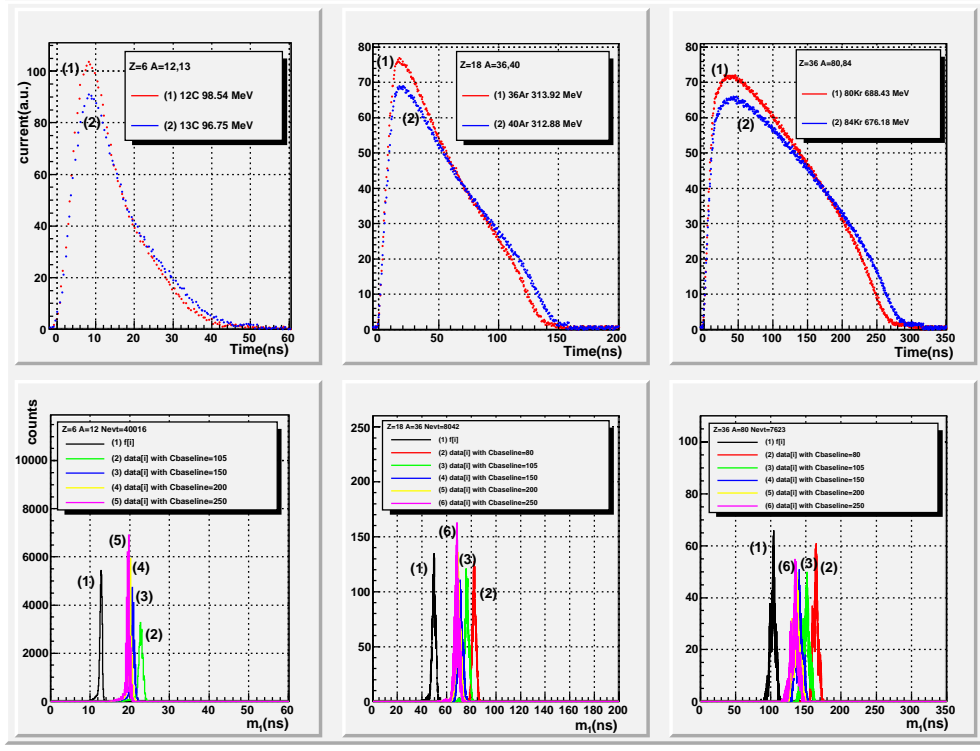


Fig. 5. Upper part: averaged signal for the 3 pairs of isotopes. Bottom part: m_1 distribution for the lighter isotope as a function of the signal configuration.

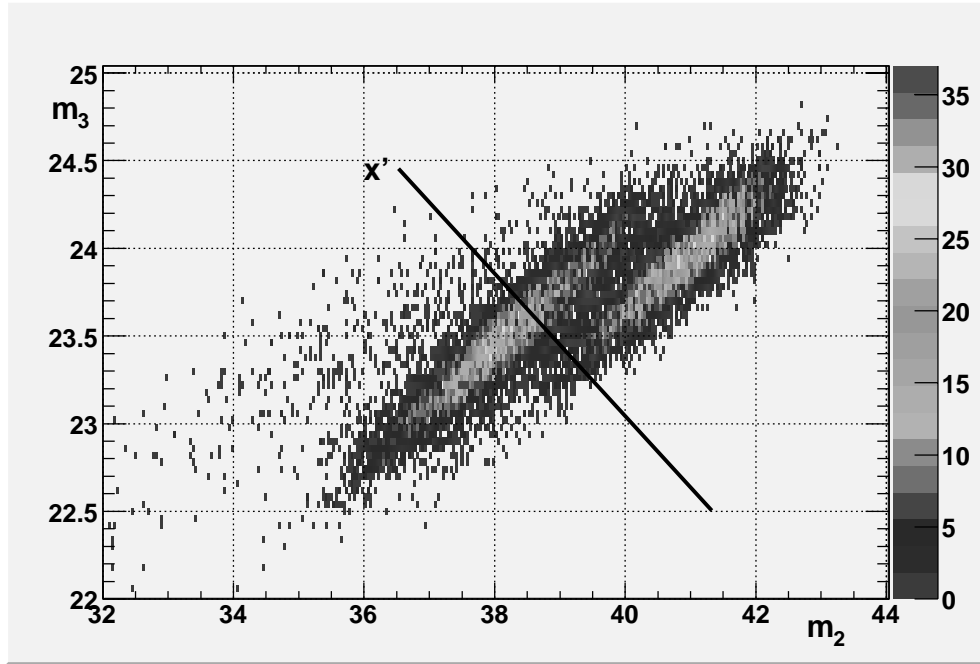


Fig. 6. Example of separation in the m_2 vs m_3 plane for Ar-isotopes.

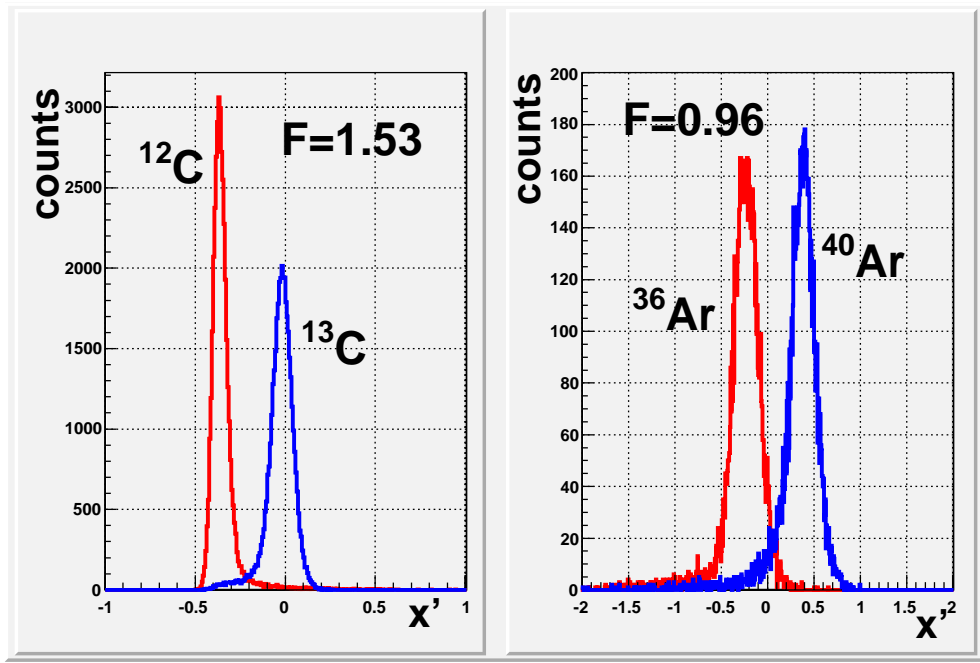


Fig. 7. Separation between ^{12}C vs ^{13}C (left part) and ^{36}Ar vs ^{40}Ar (right part) with the projection technique explained in the text.

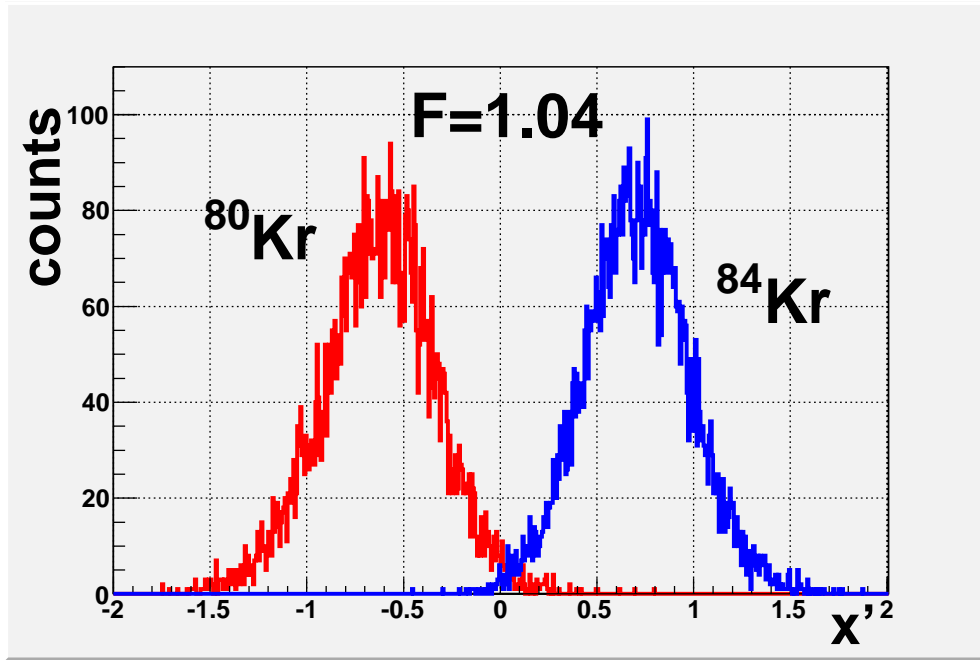


Fig. 8. Separation between ^{80}Kr vs ^{84}Kr with the projection technique explained in the text.

Method	100 MeV ^{12}C , ^{13}C	312 MeV ^{36}Ar , ^{40}Ar	682 MeV ^{80}Kr , ^{84}Kr
Amplitude max. (mA)	M=1.42	M=0.81	M=0.54
Risetime (ns)	M=0.62	M=0.36	M=0.26
Decay time (ns)	M=0.81	M=0.48	M=0.07
Slope (mA/ns)	M=1.35	M=0.73	M=0.11
m_2 (ns)	M=0.91	M=0.64	$M \approx 0$

Table 1

Merit Factor for the three pairs of ions ^{12}C vs ^{13}C , ^{36}Ar vs ^{40}Ar and ^{80}Kr vs ^{84}Kr using the "standard" discrimination methods (see text for details).

Couple of Ions	m_1 averaged using $f(i)$	m_1 averaged using $data(i)$	Signal extension
Carbon	12.8 ns	22.8 ns	45 ns
Argon	49.7 ns	71.2 ns	150 ns
Krypton	103.4 ns	164.2 ns	300 ns

Table 2

Averaged value of m_1 for ^{12}C , ^{36}Ar and ^{80}Kr using the signal in configuration $f[i]$ and $data[i]$ with the value of $C_{baseline}$ equal to 103, 155 and 83 respectively. They are compared with the extension time of the signal.

Couple of Ions	$Mean_1$	$Sigma_1$	$Mean_2$	$Sigma_2$
100 MeV $^{12}\text{C}+^{13}\text{C}$	-0.361	0.036	-0.018	0.059
312 MeV $^{36}\text{Ar}+^{40}\text{Ar}$	-0.231	0.134	0.380	0.138
682 MeV $^{80}\text{Kr}+^{84}\text{Kr}$	-0.625	0.280	0.701	0.261

Table 3

Fit values from a Gaussian fit applied to the couples of peaks shown in Fig.7 and Fig.8.

Couple of Ions	Merit Factor using $f(i)$	Merit Factor using $data(i)$
100 MeV $^{12}\text{C}+^{13}\text{C}$	1.15	1.53
312 MeV $^{36}\text{Ar}+^{40}\text{Ar}$	0.84	0.96
682 MeV $^{80}\text{Kr}+^{84}\text{Kr}$	0.50	1.04

Table 4

Table of Merit Factor for the four pairs of ions ^{12}C vs ^{13}C , ^{36}Ar vs ^{40}Ar , ^{80}Kr vs ^{84}Kr for the new discrimination method using $f(i)$ and $data(i)$ (see text for details).